Year: 2019

Bamboo: An Engineered Alternative for Buildings in the Global South

Zea Escamilla, Edwin ; Archilla, Hector ; Nuramo, Denamo Addissie ; Trujillo, David

DOI: https://doi.org/10.1007/978-3-030-12036-8_15

Originally published at:
Zea Escamilla, Edwin; Archilla, Hector; Nuramo, Denamo Addissie; Trujillo, David (2019). Bamboo: An Engineered Alternative for Buildings in the Global South. In: Guedes, Manuel Correia; Cantuaria, Gustavo. Bioclimatic Architecture in Warm Climates. Wiesbaden: Springer, 397-414.
DOI: https://doi.org/10.1007/978-3-030-12036-8_15

Bamboo, an engineered alternative for buildings in the global south.

Dear Reader, this is a pre-print version of the chapter. Some minor features and details might not appear on this document.

Pleas cite this chapter as:

Zea Escamilla, E., H. Archilla, D. A. Nuramo and D. Trujillo (2019). Bamboo: An Engineered Alternative for Buildings in the Global South. Bioclimatic Architecture in Warm Climates, Springer: 397-414.

Edwin Zea Escamilla[1*], Hector F. Archilla[2], Denamo Addissie Nuramo[3] , David Trujillo[4]

[1] Centre for corporate responsibility and sustainability at University of Zürich, Switzerland
[2] Amphibia – BASE & Visiting Research Fellow at University of Bath, UK
[3] Addis Ababa University, Ethiopian Institute of Architecture Building Construction and City Development. Addis Ababa, Ethiopia.
[4] School of Energy, Construction and Environment, Coventry University, UK
*Corresponding author: edwin.zea@ccrs.uzh.ch, Tel.: +41 788481531

1.1. Bamboos of the World

Bamboo is the only Graminea adapted to the life as forest. Bamboos can be found around the globe and are naturally occurring in Africa, America, and Asia in tropical, subtropical and warm temperate areas around the equator. Bamboo are giant grasses that propagate rapidly by the expansion of underground rhizomes. In general, bamboos are known for their rapid growth with a rate of up to 25cm/day in certain species of woody bamboos such as Guadua *angustifolia* Kunth (Bamboo). Although there are some species of solid bamboos, morphologically bamboo can be generally described as a hollow tapered tube (culm), with internodes separated by nodes, which is supported by an intricate rhizome system (Figure 1). The culm is the main organ of the aerial part of bamboos, which is also comprised of branches, sheaths and foliage leaves, with flowering occurs sporadically. The rhizome and culm neck form the subterranean part. Culms store about 80% of the carbohydrates required by young plants for their growth, whilst rhizomes store the remaining 20%.

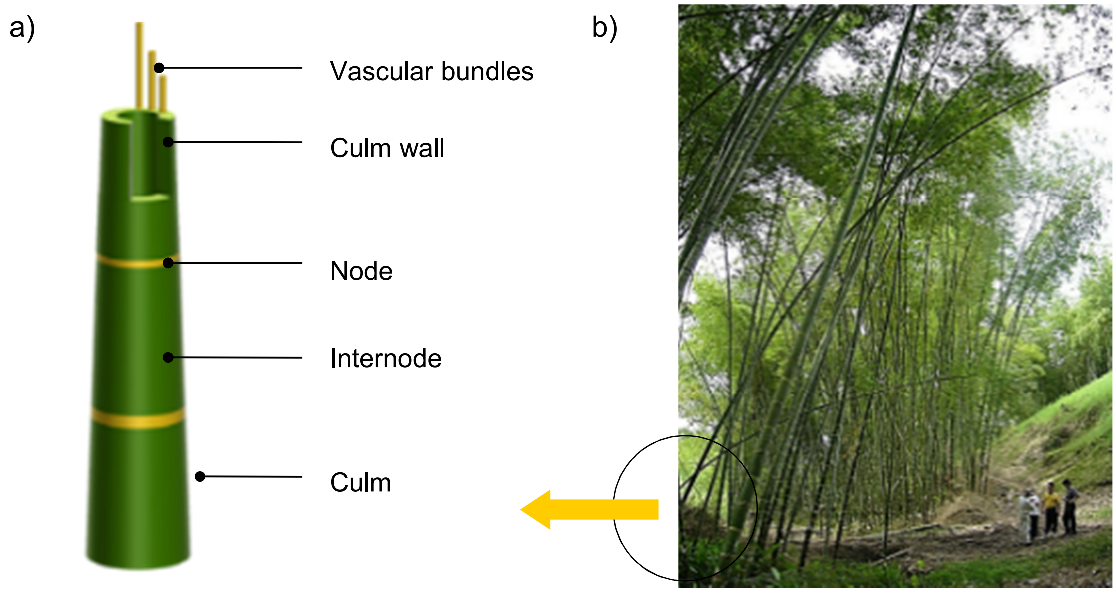


Figure 1. (a) Part of the culm, (b) Bamboo plantation [1].

The growth process of a bamboo culm differs of that of a tree. Firstly, a bamboo culm will experience a rapid growth phase in which the cane will reach its maximum height and diameter in about 9 to 12 months. Secondly, the culm starts a process of consolidation of tissues which occurs by secondary cell thickening until maturity, which results from the deposition of lignin (lignification) of acquired cell wall layers (polylamellation). This lignification of fibre-cell walls increases bamboo's density, but not its diameter or height. The plant reaches maturity in three to five years and what follows is a natural process of decay. Bamboo clumps can grow for 50 years or more, but flowering results in the death of the whole plant in some species (Liese 1998; Hidalgo-López 2003). Such delay in the flowering process is attributed to the considerable energy demand of this fast growing plant (Clark, 1997 cited by Lybeer *et al.* 2006). This, together with the resulting high biomass production give bamboo an advantage over other renewable resources in terms of yield.

Thanks to their wide availability and renewability bamboos have been used around the world for millennia for many applications ranging from food to furniture and construction. More than 1,600 species of herbaceous and woody bamboos have been catalogued [2] and about 20 species of woody bamboos are considered as key species for construction purposes[3]. For instance, the sympodial species Bamboo is used for construction in South and Central America; it has large vascular bundles (Figure 1) with fibre bundles of variable sizes that confer it with a coarse finish. In contrast, the monopodial *Phyllostachys heterocycla pubescens* (Moso) endemic to Asia is more suitable for smooth finishes for parquet, furniture and decorative applications[4]. This is due to its smaller vascular bundles with fairly even distributed fibres around the conductive tissue. Some species such as *Oligostachyum sp.* and from the genus Indocalamus are classified as amphipodal, which combines sympodial and monopodial rhizomes.

It is estimated that bamboo forests cover an area around 37 million hectares which amounts to about 4% of the world's total forest coverage[5]. From this total coverage, it is estimated that Africa has more than 40 bamboo species covering more than 1.5 million hectares[5]. Studies in utilization of bamboo in Africa have indicated that, the resource is less valued than wood products and its uses are mainly traditional and only a few manufacturing firms are reported so far[6,7]. All around Ghana bamboo culms are used both in rural and urban areas for construction purposes including fencing, scaffolding, as frames for mud houses, props, rafters, roof material, for binding thatch in roofing houses, construction of livestock pens[8]. Moreover, processed bamboo products comprising plywood bamboo, ceiling panels, flooring, window blinds, doors and furniture are produced and used in Ghana[8]. In Nigeria bamboo is distributed widely in the south and middle belt regions where the average diameter of the bamboo culms ranges from 3.2 to 9.1 cm[9]. It is reported that the rate of use of bamboo in Nigeria is low[9]. Traditionally, bamboo is used for scaffolding, shade houses, fencing, and furniture making[10]. It is also used in rural areas to construct mud houses where bamboo culms serve as structural frames[9]. Other uses of bamboo for construction in Nigeria includes structural element for buildings, bamboo based panels, and furniture[10]. There are two indigenous bamboo species in Ethiopia covering more than 1million hectares of land. In the rural areas of Ethiopia where bamboo grows, people use bamboo culms for construction of houses, construction of fences, and furniture making[11]. While Ethiopia has a huge bamboo resource, its utilization for construction purposes has been limited to hut construction, fencing, furniture and handicrafts[12].

1.2. Bamboo use

Bamboo uses can then be classified depending on the degree of transformation of the raw material and the manufacturing process to which it has been subjected. Three material transformation stages are identified: non-processed, moderately processed and highly processed in Figure 2. This figure illustrates the processes applied to bamboo and the transformation stage attained for certain applications. Overall, traditional uses require less intensive processing, whilst industrialised uses require high levels of transformation.

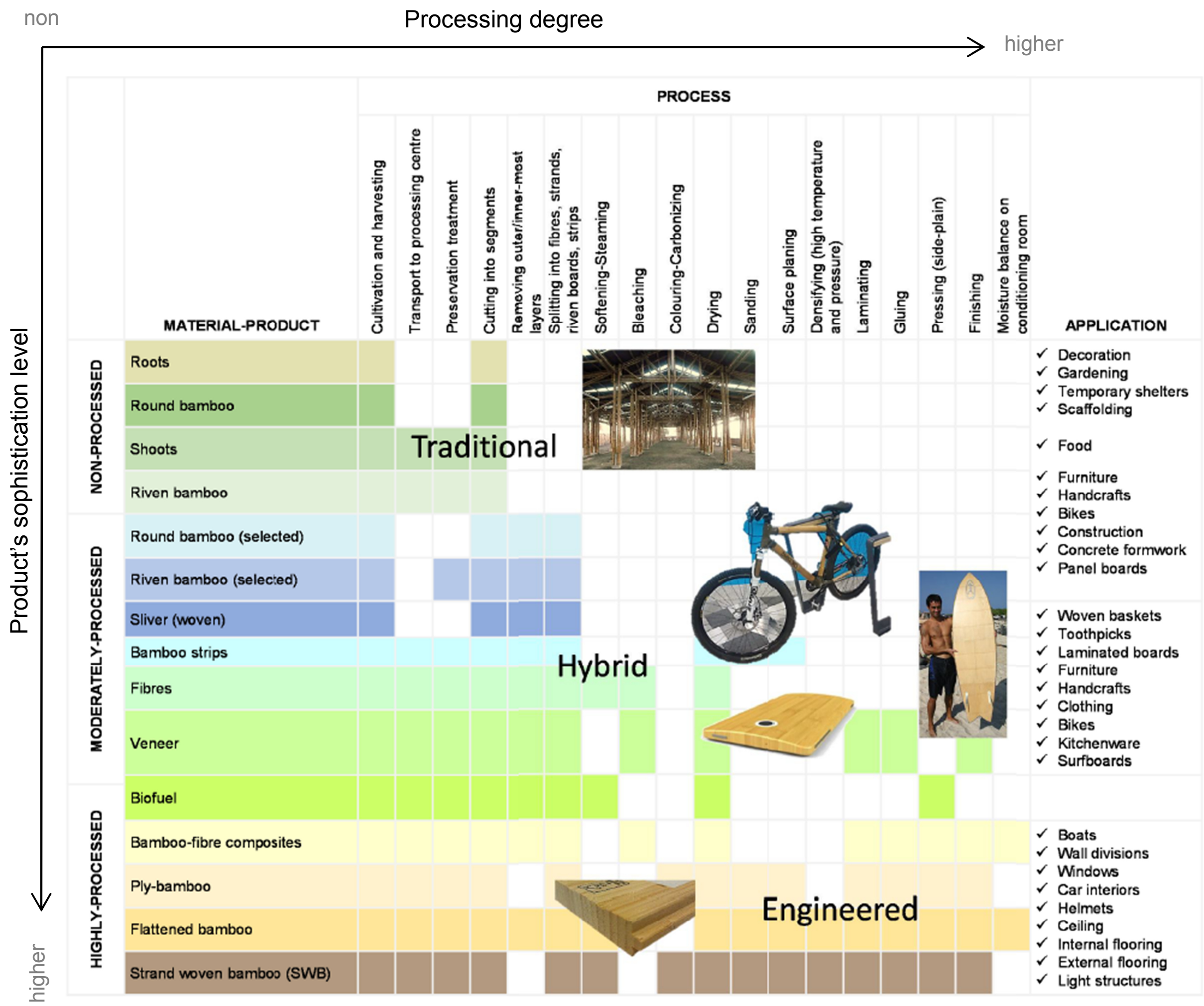


Figure 2. Uses of bamboo depending on its transformation degree [1]

Non-processed raw bamboo is commonly used for low added value and short-term applications (temporary shelters, scaffolding, handcrafts, food, etc.) usually where the material is abundant and durability is not a concern –because rotten material can be easily replaced. Moderately processed mature bamboo is preserved and dried mainly for its use in traditional construction in countries where bamboo-building systems (Bamboo) are regularized (e.g. Colombia, Ecuador, Peru and Mexico). In addition, some handcrafts and furniture applications make use of these type of bamboo in which, manual and non-intensive industrial processes are involved (hybrid). Engineered bamboo products (EBPs) are highly processed bamboo products that add high value to the plant through different transformation processes resulting on consistent, straight-edged products. Some of the most popular engineered bamboo products used in construction are: flooring (e.g. flattened bamboo), architectural surfaces (e.g. bamboo plywood or plyboo) and exterior decking (e.g. strand woven bamboo-SWB). The Chinese industry is the main supplier of these products with Moso-bamboo as the raw material. Finally, some hybrid bamboo products are made by combining different processing stages to achieve aesthetic appeal.

1.3. Traditional bamboo-based construction material

Although non-processed bamboo canes (culms) are broadly used in construction, should not be considered as construction material in itself. It is estimated that more than a billion people live in bamboo houses worldwide. In Bangladesh alone, more than 70% of the houses use non-processed bamboo culms in walls and roof structures in a temporary fashion.

Bamboo culms are the main input for all the bamboo-based construction materials and can be processed into five distinctive types of bamboo-based construction materials. They can be roughly divided between moderately industrialised materials (e.g. (i) preserved and dried bamboo poles, (ii) flattened bamboo -*esterilla*-, (iii) woven bamboo mats and (iv) strips) [13,14]. These categories are presented on Figure 3**.**

(i) Bamboo poles are derived directly from the bamboo culm and are usually trimmed in sections between three and six metres and treated against fungi and pest using boric acid (H_3BO_3 or $B(OH)_3$) and borax (sodium borate) for 7-10 days. Poles are then dried until its moisture content is below 20%. The poles are then transported from the treatment plant to either a distributor or to an intermediate processing facility. This transport is generally local with a range between 4km and 120km[13]. Preserved and dried bamboo poles can be used directly in construction as columns, beams, or struts and are also the main input for the production of flattened bamboo, woven mats, strips, slivers, strands and other starting materials for engineered bamboo products [13,15].

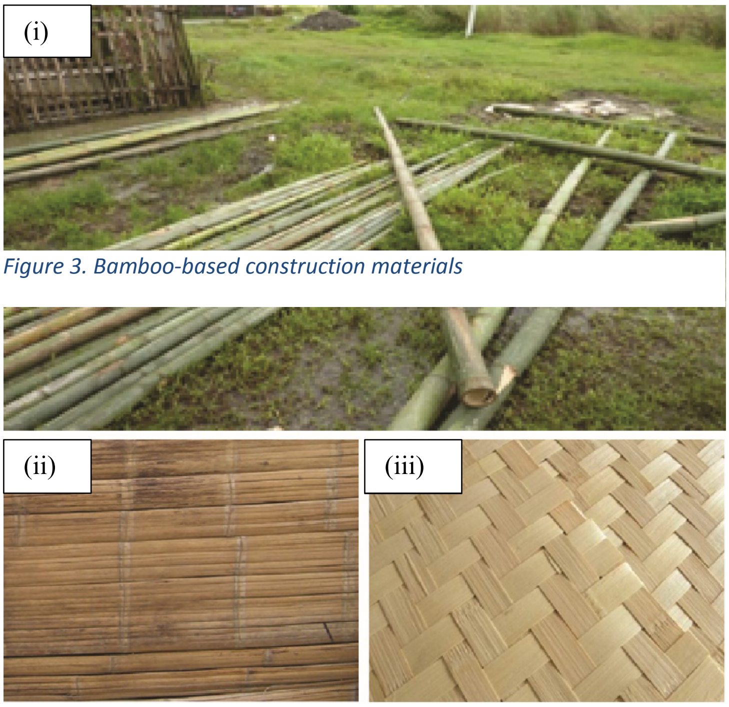


Figure 3. Bamboo-based construction materials

(ii) Flattened bamboo is a handcrafted construction material. To produce flattened bamboo, a bamboo pole is split open with an axe and its innermost part and internodes are removed. During this process some fibres are broken making the material flexible, but still able to maintain its ‘mat-like’ shape [13,14]. The main application of flattened bamboo is in load-bearing wall systems, where it is used between bamboo poles in order to support the soil cement mortar with which the walls are plastered.

(iii) Woven bamboo mats, are produced by manually or mechanically splitting a bamboo pole into strips with widths between 2cm and 4cm. These strips are then reduced by hand or in a slivering machine into thinner elements with thicknesses between 0.5mm and 3.5mm (Liu et al. 2016), which are then woven to form a mat [14]. The entire process is usually done manually in small rural communities. The woven bamboo mats are generally used as lightweight walls, but recently they have also been used to produce panels of EBP in India [13] (although, their manufacturing process is still labour and glue intensive). Flattened bamboo and woven bamboo mats are commonly manufactured in facilities very close to the point of extraction and/or treatment.

1.4. Engineered bamboo

Bamboo can be engineered to form products with improved and/or standardised mechanical, physical and aesthetic properties. The transformation of naturally variable bamboo culms into engineered products with predictable properties and generally rectangular shapes facilitates the mainstream use of bamboo in construction. In general, engineered bamboo products (EBP) are scarce and require intense processing. Their development started with the manufacture of bamboo panel boards in China around 1940; however, it was not until the end of the last century, during the 80s and 90s, that research and commercial interest in this type of materials increased [16]. Currently, the use of the bamboo species: Phyllostachys heterocycla pubescens (Moso) for the production of EBP is widespread. Liu et al. [14] and Archilla and Trujillo [17] classifies EBPs into three main types: (i) laminated bamboo, (ii) densified bamboo, and (iii) bamboo boards.

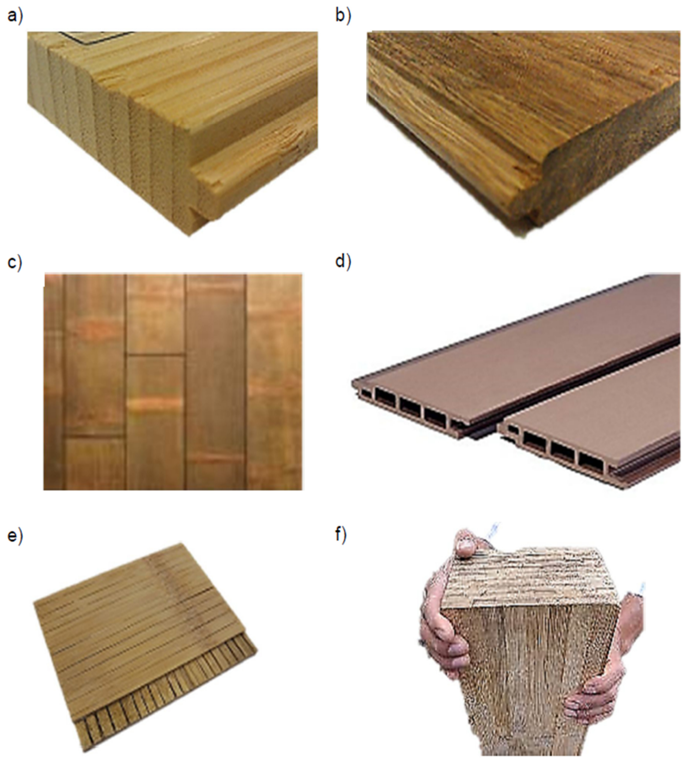


Figure 4. Engineered bamboo products. ***Laminated bamboo****: a) Ply-bamboo and c) Flattened half-bamboo poles (MOSO International B.V.) and f) Glue-laminated Bamboo beams (www.agenciadenoticias.unal.edu.co).* ***Densified bamboo****: b) SWB,; and other EBPs developed using Moso and Bamboo, respectively: d) Bamboo plastic composite (www.bambooindustry.com), and e) Glue-laminated flattened Bamboo boards.*

As illustrated in Figure 4, commercially available EBPs such as glue-laminated bamboo strips (a) and (f), densified strand woven bamboo or SWB (b) and bamboo boards such as those made out of flattened half-bamboo poles (c), fibres (d), flattened mats (e) and bamboo strands or particles are industrially manufactured mainly in China through several processing stages and possess distinctive mechanical properties (Table 1Figure 2). Due to their elevated degree of transformation these EBP are referred to as highly processed bamboo products in Figure 2.

Currently, the most widespread practices in the manufacturing of EBP are the machining and lamination of longitudinal strips and the hot-pressing of fibre strands under elevated temperatures (Table 1). The former refers to the process undertaken to manufacture laminated bamboo products and the latter the process undertaken for SWB, a densified bamboo product.

Table 1. Processes involved in the manufacture of some engineered bamboo products and their mechanical properties[18-23].

	Product	Density kg/m³	Species	Process	MOE Bending GPa	MOR Bending MPa
Lamination Strips	Sulastiningsih & Nurwati [1]	710-750	G. apus/ G. robusta	Cold press+ clamped	7 - 10	39 - 95
	Mahdavi *et al.*,[2]	510	Moso	Cold press	9	77
	Plybamboo (Plyboo) [3]	666	Moso	Cold press	-	135
	Laminated Guadua [4]	728 - 796		Cold press	-	82
	Xiao *et al.*, 2013 [5]	800 - 980	Moso	Hot press	9	99
	Flattened bamboo [3]	850		Steam + Hot press	-	-
Hot pressing Fibre strands	LBL (zephyr mat) [1]	940	Moso	Roller crushing + Hot press	10.1 - 11.6	66.5 - 81.2
	Bamboo scrimber [6]	1240	*Melocanna Baccifera*	Roller crushing + Glue im-pregnation + Hot press	15.2	266
	Huang *et al* [7]			Hot press	13	89
	SWB outdoor [3]	1,200	Moso	Hot press	-	-

[1] (Sulastiningsih & Nurwati, 2009) [2] (Mahdavi *et al.*, 2011) [3] MOSO International BV (Vogtländer & van der Lugt, 2014) [4] (Correal *et al.*, 2014) [5] (Xiao *et al.*, 2013) [6] (Nugroho & Ando, 2000) [7] (Huang *et al.*, 2013)

During the strip lamination process, the round culm is first split into six to eight concentric sections; secondly, the trapezoidal-like section of the strips is sanded down into a rectangular form after removal of about two thirds of the total material and finally the strips are longitudinally oriented and glue laminated into beams, boards or flooring slats. One of the biggest drawbacks of this process is the high amount of material discarded. Usually, the strongly consolidated outer layer of the bamboo culm with the highest specific gravity is removed and its mechanical properties are no longer comparable to steel. The negative influence on the mechanical properties of bamboo due to removal of the outer skin as well as the considerable material wasted through the strip lamination process has been highlighted by Nakajima et al. [24] Tanaka et al. [25] and (Archila 2015). These studies have undertaken modifications to the cell structure of bamboo by thermal softening, the first without pressure , the second with elevated temperature and pressure and the third with moderated heat and pressure. These type of heat and pressure treatments are currently applied to bamboo with the aim of achieving flat sections of high density and hardness. Some of the resulting mechanical properties of lamination and heat and pressure processes applied to bamboo are presented in Table 1.

1.5. Bamboo based buildings

Bamboo has been used as a construction material for centuries all over the world and traditional bamboo building systems have been widespread mainly in Africa, Asia and Latin-America [26,27]. Earthquake prone countries such as Colombia, Ecuador and Peru, have adopted bamboo culms as a structural material within their building codes for walling and framing systems of up to two storeys [28,29].

According to a study by INBAR[30], utilization of bamboo as a construction material in Ethiopia relates to the construction of traditional or rural housing where only 2.5% of those housing units are constructed from bamboo. Studies have shown that there were more than 500,000 units of houses constructed out of bamboo in Ethiopia in 2007.

Ethiopia has a rich tradition of constructing houses with bamboo using traditional techniques. Below are pictures of some of the traditional bamboo houses in Ethiopia.

Fig 1 Dorze bamboo house

Fig 2 Sidama bamboo house

Plastered cane building system (*Bahareque encementado*)

The plastered cane building system is the most common structural bamboo system. It consists of load bearing bamboo walls that are plastered with cement mortar for weathering protection, structural integrity and improving its fire-performance [31]. This structural wall framing system with bamboo for one and two storey dwellings was firstly normalised by the Colombian construction code, today known as NSR-10. It is defined as a system composed of a Bamboo or Bamboo and timber skeleton, and a sheathing made out of flattened Bamboo (Figure 5), nailed to the skeleton and covered with a cement render applied over a steel mesh [28]. Both elements together result in a shear wall response.

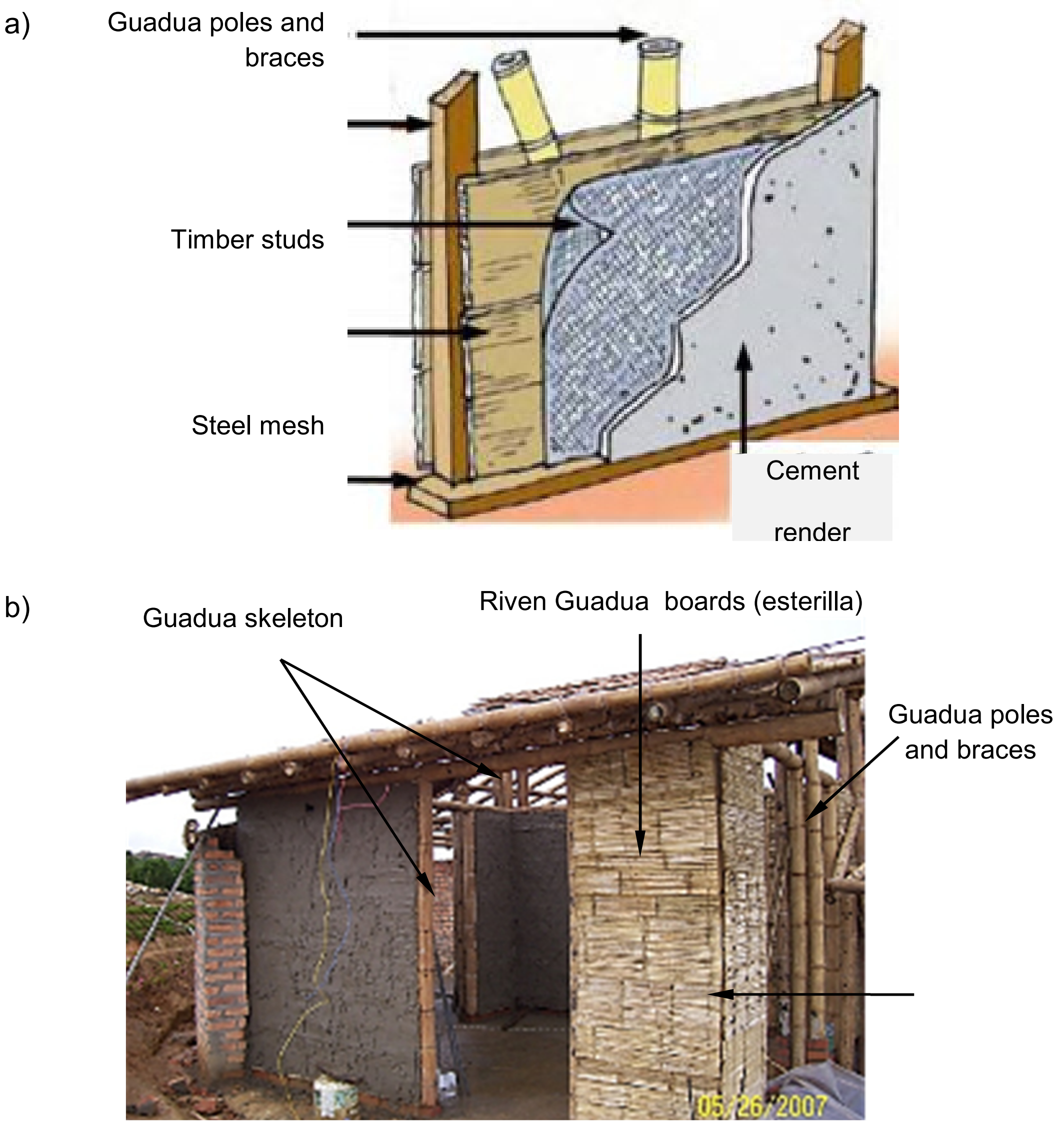
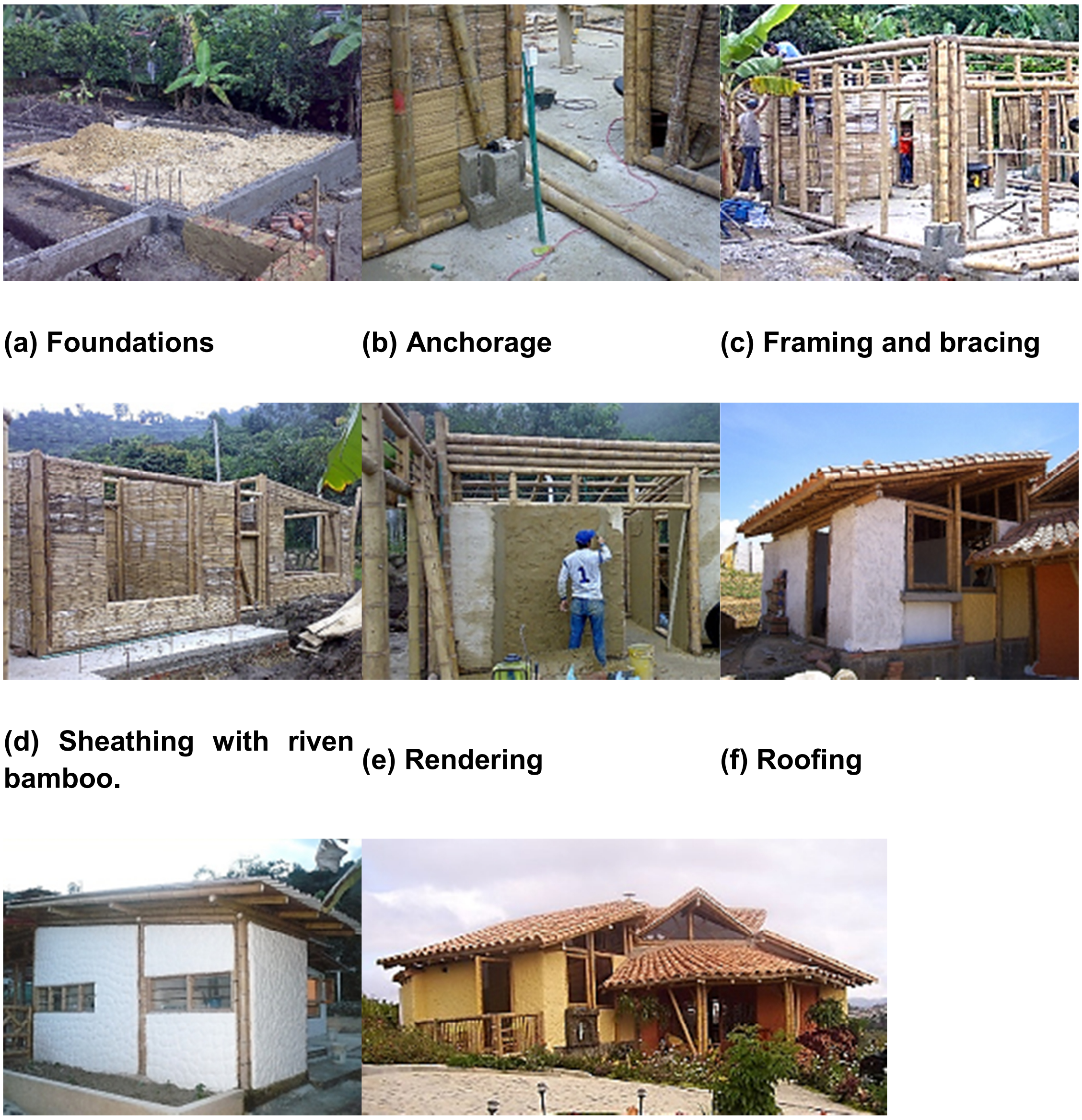


Figure 5. Plastered cane wall-framing system with parts diagram. Image (a) taken from (AIS & FOREC 2002a)

This system uses Bamboo intensively (approx. 12 linear meters per sq. meter) where 50% of the material is round Bamboo used for the skeleton (frame) and the other 50% is riven Bamboo boards used for the sheathing. Different configurations of walls depend on their function and structural performance. Structural braced walls are designed to resist vertical, horizontal and wind loads and must be located on the corners of the building and at the ends of every set of structural walls. Non-braced structural walls withstand vertical loads and must not be located at the ends of the wall system. In addition, non-structural walls are used as divisor walls and must not bear any shear or vertical loads (do not need to be continuous or to be anchored to the foundations). A series of images in **Fehler! Verweisquelle konnte nicht gefunden werden.** depict the building process with this Bamboo wall framing system.



(a) Foundations (b) Anchorage (c) Framing and bracing

(d) Sheathing with riven bamboo. (e) Rendering (f) Roofing

(g) Finishing (h) Final product

Figure 6. Construction process of the plastered cane wall framing system (picture (h) by Arme Ideas en Bamboo Ltd).

Within the frame structure, head and sole plates in timber are strongly recommended instead of Bamboo due to crushing perpendicular to the grain (see Figure 5); these constitute the horizontal elements. The studs must be separated by between 300 mm and 600 mm and the diameter of Bamboo must not be less than 80 mm. The diameter of the steel wire mesh nailed to the flattened Bamboo must not exceed 1.25 mm (curtain mesh). The sheathing of the wall skeleton should be applied to both sides.

Overall, this system has been conceived to: a) minimize the effect of collapse during strong seismic events of low probability; b) ensure low damage during moderate seismic events; and c) avoid any damage from minor seismic events of high probability. Therefore, slab, roofs, columns and additional structural elements must be designed to contribute to the stability of the main load bearing system, following the requirements for each variation considered within the Colombian Code for seismic resistant construction As stated previously, this system is restricted to two storey buildings.

However, the two main limitations of this system are a) its current maximum height limitation to two storeys and b) that it uses a significant amount of cement, aggregates and steel for the reinforcement and plaster of the walls c) the use of whole bamboo culms makes construction processes labour intensive [31,32]. These points render it unsuitable for multi-story buildings that can cope with the need for high density construction in growing urban centres, whereas the latter corresponds to about 50% of the total environmental impact of the construction, which increases its overall carbon footprint.

Framing systems for large structures with Bamboo

The infill of Bamboo internodes with a cement mortar (Figure 7) has led to increased rigidity of the connections, which otherwise will fail by shear parallel to the grain or crushing perpendicular to the grain.

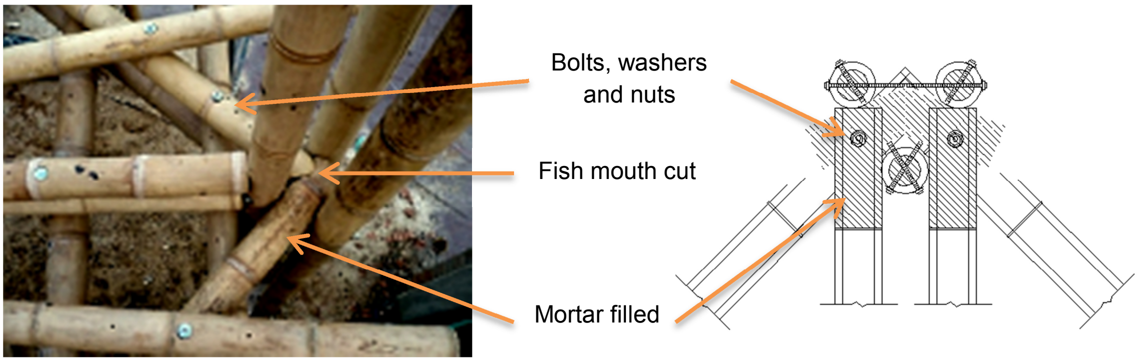


Figure 7. Detail of connections in a Bamboo structure

This gain in rigidity has allowed the construction of large structural frames for commercial and institutional buildings and hybrid structures for holiday houses such as those in Figure 8 a) and b), respectively.

Others structures have demonstrated the potential of round poles of Bamboo as an engineering material for large structures using in-filled internodes and comparable structural concepts to the traditional collar and tie initially introduced by Simón Vélez. These include the replica of the Indian Pavilion for the Shanghai Expo 2010 (Figure 9,) recently built in Bogotá , the Zeri Pavilion for the Expo Hannover in 2001 and a pedestrian bridge in Holland.

a) b)

Figure 8. a) Warehouse in Bogotá, Colombia by Hector Archila. b) Bohio, holiday cottage in Villeta, Colombia by Hector Archila.

a) b)

Figure 9. Replica of the Indian pavilion for Expo-Shangai 2010 by Simón Vélez in Bogotá, 2014. a) Interior view of the structure. b). Exterior view.

1.6. Environmental issues

The current practices in the construction sector make use of increasingly larger amounts of energy and are responsible for the depletion of natural resources [33]. The levels of extraction of construction minerals has also reached new levels in the XXI century, highlighting not only the problem of the availability, but also the accessibility to those resources[34]. For instance, the production of construction materials such as cement and aggregates is using 30 to 40% of global energy production [35] and under the current practices it means that their production process releases 30% of global GHG emissions [36,37]. Therefore, it is imperative to explore the potential environmental benefits from the use of low-carbon alternative construction materials, amongst these bio-based materials such as bamboo and timber. Bio-based construction materials are renewable and with adequate management their production can be sustained over long periods of time. Moreover, during their growth phase they capture atmospheric CO_2 and store it in their tissues [38,39]. If these materials are used in durable products, such as buildings and their constituent materials, then the release of the captured CO_2 can be delayed as long as the buildings are in service [40]. In the case of bamboo, due to its heterogeneous growth only 25% of the culms are harvested annually [38]. As a result, a plantation is always standing, capturing CO_2 and producing readily feedstock for its potential use as construction material [38].

The environmental impacts of bamboo-based construction materials increase in relation to their level of industrialization[13]. A significant difference in environmental impact can be observed between industrialized and hand crafted products. The environmental impact of bamboo pole is, for example, five times smaller than the impact associated with glue laminated bamboo. In the cases of handcrafted materials such as flattened bamboo and woven bamboo mats, the environmental impacts increase only due to the material demand associated with their production. To better understand the environmental impacts presented here, it is necessary to look at the relative contribution of the different processes involved in a material's production. Flattened bamboo and woven bamboo mat are handcrafted from bamboo poles and thus have only one input. Consequently, they have only one process contributing to environmental impact. For the low industrialized materials, the contribution of the raw material production, the growth of bamboo culm, represents less than 10% of the total impact as presented in **Figure 4**. The drying process is the major contributor with 35%, followed by the electricity used for trimming with 25% and the treatment for insect resistance with a 15% share of the total. The contribution associated with infrastructure and machinery is much higher for the low industrialized materials than for the highly industrialized ones, with contributions to the total impact of 12% and 2% respectively

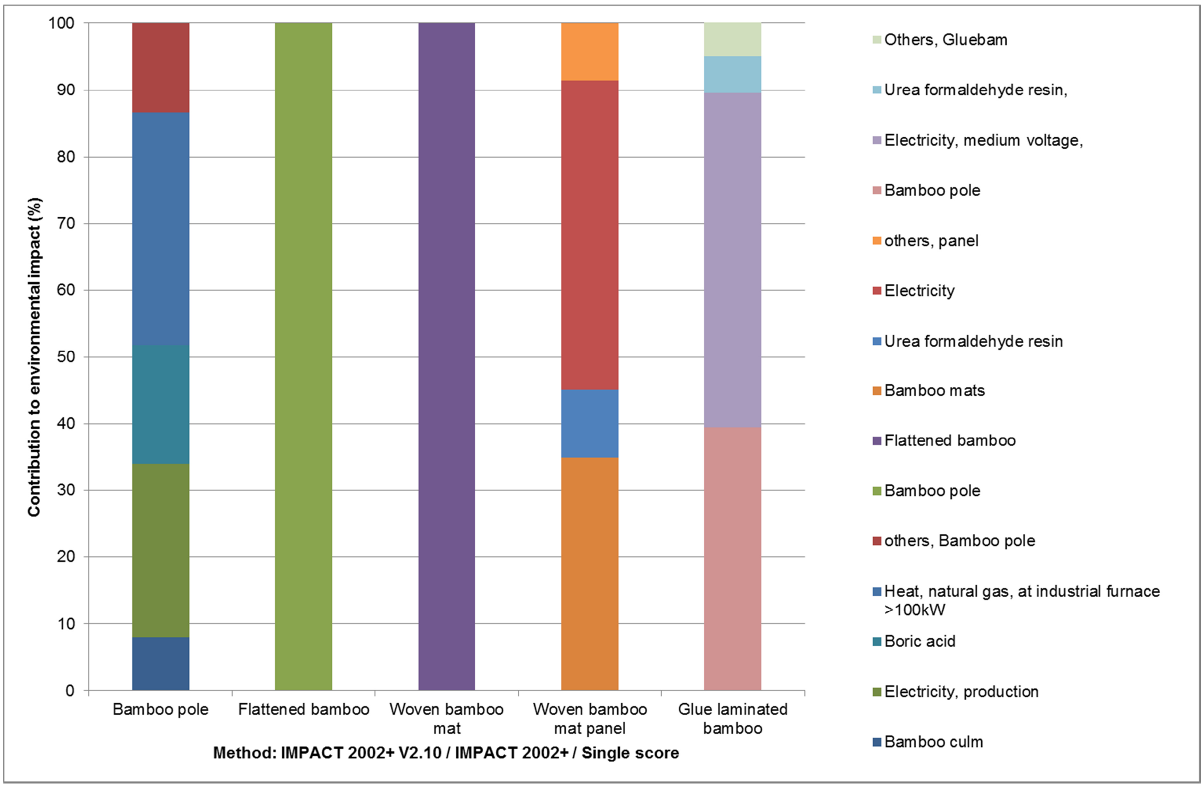


Figure 10 Contribution to environmental impact

In order to compare the environmental impact of different construction materials it is necessary to do it at the building level. This is due to the differences in services that a unit of materials can provide. The work of Zea et al.[41] has shown that bamboo-based buildings using either handcrafted or engineered bamboo products withhold great potential to produce lower environmental impacts than those constructed with mineral based materials, as shown on Figure 4

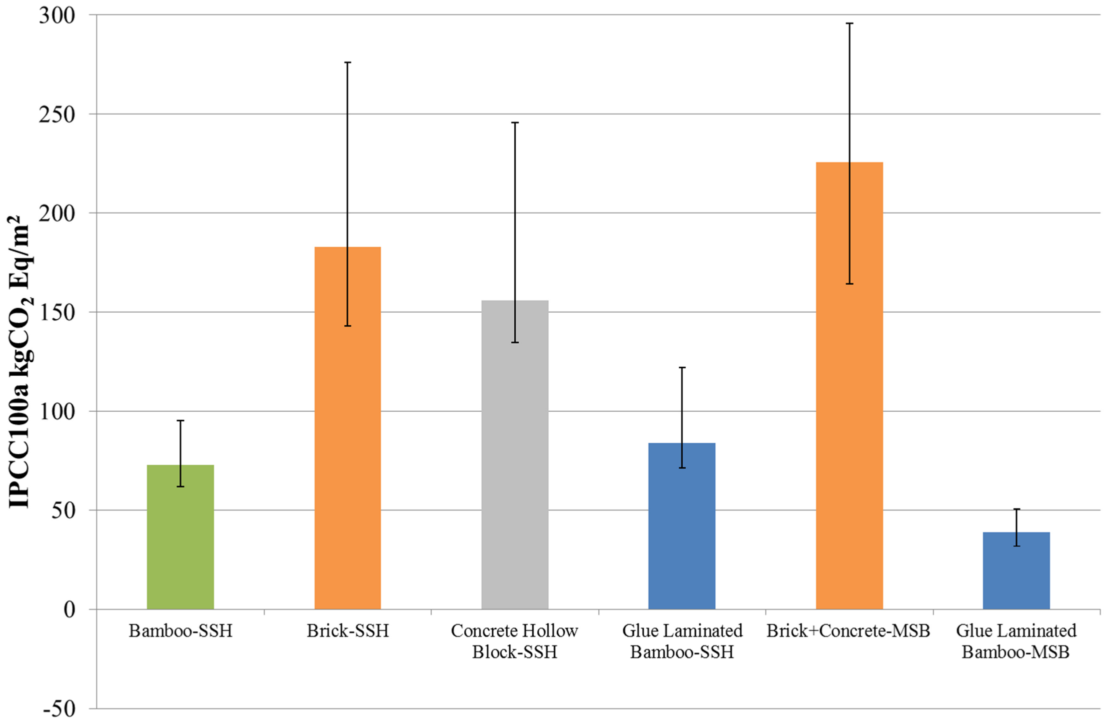


Figure 11 Environmental impact kgCO2Eq. (SSH): Single Storey House; (MSB): Multi Storey Building.

These environmental benefits go beyond the reduced emissions from the production of materials and construction of buildings. If the whole life cycle of the bamboo-based building, from bamboo plantation to recycling of the building's material, it becomes that bamboo withholds a great potential as storage of CO_2. As an example, the CO_2 flows associated with the execution of industrialized bamboo-based housing solutions are presented in Figure 5. This figure shows two types of temporary CO_2 storage (captured in the plantation and stored in buildings) and two types of avoided CO2 emissions (avoided from electricity generation by using material by-products and the recycling of demolished construction materials). The implementation of an industrialized bamboo-based housing program exerts positive effects on the environment by capturing and avoiding over 10^8 tCO_2e emissions over 130 years.

The use of in construction can support the regenerative development of the regions in which they are applied, leading to sustained improvements in their environment and economic stability

REFERENCES

1. Archila Santos, H.F. Thermo-hydro-mechanically modified cross-laminated guadua-bamboo panels. University of Bath, 2015.
2. Vorontsova, M.S.; Clark, L.G.; Dransfield, J.; Govaerts, R.; Baker, W.J. *World checklist of bamboos and rattans*. Science Press: 2017.
3. Ramanuja Rao, I.V.; Sastry, C.B. *Bamboo, people and the environment: Proceedings of the vth international bamboo workshop and the iv international bamboo congress, ubud, bali, indonesia, 19-22 june 1995*. International Network for Bamboo and Rattan: India, 1996.
4. Liese, W. *The anatomy of bamboo culms*. Brill: 1998; Vol. 18.

5. Phimmachanh, S.; Ying, Z.; Beckline, M. Bamboo resources utilization: A potential source of income to support rural livelihoods. *Applied Ecology and Environmental Sciences* **2015**, *3*, 176-183.
6. Endalamaw, T.B.; Lindner, A.; Pretzsch, J. Indicators and determinants of small-scale bamboo commercialization in ethiopia. *Forests* **2013**, *4*, 710-729.
7. Ingram, V.; Tieguhong, J.C. Bars to jars: Bamboo value chains in cameroon. *Ambio* **2013**, *42*, 320-333.
8. Obiri, B.D.; Oteng-Amoako, A. Towards a sustainable development of the bamboo industry in ghana. *Ghana journal of Forestry* **2007**, *21*, 14-27.
9. Atanda, J. Environmental impacts of bamboo as a substitute constructional material in nigeria. *Case Studies in Construction Materials* **2015**, *3*, 33-39.
10. Ladapo, H.; Oyegoke, O.; Bello, R. Utilization of vast nigeria's bamboo resources for economic growth: A review. *Journal of Research in Forestry, Wildlife and Environment* **2017**, *9*, 29-35.
11. Desalegn, G.; Tadesse, W. Resource potential of bamboo, challenges and future directions towards sustainable management and utilization in ethiopia. *Forest Systems* **2014**, *23*, 294-299.
12. KINDU, Y.M.M. Status of bamboo resource development, utilisation and research in ethiopia: A review. *Ethiopian Journal of Natural Resources* **2010**, *1*, 79-98.
13. Zea Escamilla, E.; Habert, G. Environmental impacts of bamboo-based construction materials representing global production diversity. *J CLEAN PROD* **2014**.
14. Liu, X.; Smith, G.D.; Jiang, Z.; Bock, M.C.; Boeck, F.; Frith, O.; Gatóo, A.; Liu, K.; Mulligan, H.; Semple, K.E. Nomenclature for engineered bamboo. *BioResources* **2015**, *11*, 1141-1161.
15. De Flander, K.; Rovers, R. One laminated bamboo-frame house per hectare per year. *Construction and Building Materials* **2009**, *23*, 210-218.
16. Ganapathy, P.; Huan-Ming, Z.; Zoolagud, S.; Turcke, D.; Espiloy, Z. Bamboo panel boards a state-of-the-art review. *Network* **1999**.
17. Trujillo, D.; Archila, H.F. *Engineered bamboo and bamboo engineering*; TRADA: High Wycombe, Buckinghamshire, UK, 2016.
18. Sulastiningsih, I.; Nurwati. Physical and mechanical properties of laminated bamboo board. *Journal of Tropical Forest Science* **2009**, 246-251.
19. Mahdavi, M.; Clouston, P.; Arwade, S. Development of laminated bamboo lumber: Review of processing, performance, and economical considerations. *Journal of Materials in Civil Engineering* **2010**, *23*, 1036-1042.
20. Vogtländer, J.G.; van der Velden, N.M.; van der Lugt, P. Carbon sequestration in lca, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo. *Int. J. Life Cycle Assess.* **2014**, *19*, 13-23.
21. Correal, J.F.; Echeverry, J.S.; Ramírez, F.; Yamín, L.E. Experimental evaluation of physical and mechanical properties of glued laminated guadua angustifolia kunth. *Construction and Building Materials* **2014**, *73*, 105-112.
22. Nugroho, N.; Ando, N. Development of structural composite products made from bamboo i: Fundamental properties of bamboo zephyr board. *Journal of wood science* **2000**, *46*, 68.
23. Huang, T.; Shi, F.; Tanikawa, H.; Fei, J.; Han, J. Materials demand and environmental impact of buildings construction and demolition in china based on dynamic material flow analysis. *Resources, Conservation and Recycling* **2013**, *72*, 91-101.
24. Nakajima, M.; Furuta, Y.; Ishimaru, Y. Thermal-softening properties and cooling set of water-saturated bamboo within proportional limit. *Journal of wood science* **2008**, *54*, 278-284.
25. Tanaka, K.; Ishitani, J.; Inoue, M. Improvement of strength performance for bamboo connector by densified technique. *Journal of Structural and Construction Engineering (Transactions of AIJ)* **2008**, *73*, 1805-1812.
26. Archila-Santos, H.F.; Ansell, M.P.; Walker, P. In *Low carbon construction using guadua bamboo in colombia*, Key Engineering Materials, 2012; Trans Tech Publ: pp 127-134.
27. Correal, J. Bamboo design and construction 14. *Nonconventional and Vernacular Construction Materials: Characterisation, Properties and Applications* **2016**, 393.

28. AIS. *Colombian code for seismic design and construction, nsr-10*; Seismic Engineering Colombian Association: Bogotá, Colombia, 2004.
29. Mena, J.; Vera, S.; Correal, J.F.; Lopez, M. Assessment of fire reaction and fire resistance of guadua angustifolia kunth bamboo. *Construction and Building Materials* **2012**, *27*, 60-65.
30. van Dam, J.E.; Elbersen, H.W.; Montaño, C.M.D. Bamboo production for industrial utilization. In *Perennial grasses for bioenergy and bioproducts*, Elsevier: 2018; pp 175-216.
31. Zea Escamilla, E.; Habert, G.; Lopez Muñoz, L.F. Environmental savings potential from the use of bahareque (mortar cement plastered bamboo) in switzerland. *Key Engineering Materials* **2014**, *600*, 21-33.
32. Murphy, R.J.; Trujillo, D.; Londoño, X. In *Life cycle assessment (lca) of a guadua house*, International Symposium of bamboo -- Guadua, Pereira, Colombia, 2004; Pereira, Colombia.
33. Bribián, I.Z.; Capilla, A.V.; Usón, A.A. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *BUILD ENVIRON* **2011**, *46*, 1133-1140.
34. Steinberger, J.K.; Krausmann, F.; Eisenmenger, N. Global patterns of materials use: A socioeconomic and geophysical analysis. *Ecological Economics* **2010**, *69*, 1148-1158.
35. Dean, B.; Dulac, J.; Petrichenko, K.; Graham, P. *The global status report 2016 - gabc*; UNEP, GABC: Paris, 2016.
36. Di Placido, A.M.; Pressnail, K.D.; Touchie, M.F. Exceeding the ontario building code for low-rise residential buildings: Economic and environmental implications. *BUILD ENVIRON* **2014**, *77*, 40-49.
37. Pearce, A.; Ahn, Y.H. *Sustainable buildings and infrastructure: Paths to the future*. Routledge: 2013.
38. Riaño, N.M.; Londoño, X.; López, Y.; Gómez, J.H. Plant growth and biomass distribution on guadua angustifolia kunth in relation to ageing in the valle del cauca – colombia. *Bamboo Science and Culture* **2002**, *16*, 43-51.
39. Asif, M. Sustainability of timber, wood and bamboo in construction. *Sustainability of Construction Materials; Khatib, JM, Ed.; Woodhead Publishing: Cambridge, UK* **2009**, 31-54.
40. Tellnes, L.G.; Gobakken, L.R.; Flæte, P.O.; Alfredsen, G. Carbon footprint including effect of carbon storage for selected wooden facade materials. *Wood material science & engineering* **2014**, *9*, 139-143.
41. Zea Escamilla, E.; Habert, G. Method and application of characterisation of life cycle impact data of construction materials using geographic information systems. *INT J LIFE CYCLE ASS* **2016**, 1-10.